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14. ABSTRACT

The research results in this report are part of an effort to enable a systematic on-line use of optimization for real-time applications in stochastic environments that bypasses intensive computation and time-consuming simulation and recognizes requirements for systems critical to the national infrastructure and the emerging information-based, network-centric view of warfare. The main outcomes of the project are: (a) Asynchronous distributed optimization schemes that use event-driven communication among system components, thus minimizing the energy used and security vulnerabilities while incurring no performance degradation. (b) A new approach for simulation-based optimization where the order of performance estimation followed by optimization is reversed leading to reduction in computational complexity by orders of magnitude. (c) Receding Horizon algorithms handling both randomness and combinatorial complexity through temporal decomposition. (d) Abstraction of complex stochastic systems into stochastic hybrid models for which the use of Infinitesimal Perturbation Analysis enables efficient gradient-based optimization.

15. SUBJECT TERMS

Distributed Optimization Algorithms, Asynchronous Optimization Algorithms, Event-driven Optimization, Simulation-based Optimization, Autonomous Agents, Cooperative Systems, Perturbation Analysis, Stochastic Hybrid Systems

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FINAL REPORT

AFOSR GRANT: FA9550-09-1-0095

TITLE: **REAL-TIME OPTIMIZATION IN COMPLEX STOCHASTIC ENVIRONMENTS**

REPORTING PERIOD: March 2009 – December 2011

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1. OBJECTIVES

The research pursued under grant FA9550-09-1-0095 has been aimed at enabling a systematic on-line use of optimization for real-time applications in stochastic environments. In stochastic settings with complex system dynamics, optimization is largely used as an off-line methodology since it requires intensive computation and often time-consuming simulation. This work seeks to develop an optimization framework that addresses this limitation while recognizing requirements for new generations of systems critical to the national infrastructure and consistent with the emerging information-based, network-centric view of warfare.

Four major research objectives have been pursued:

1. **Asynchronous distributed optimization**. Distributed optimization schemes are necessary to ensure scalability and to accommodate the limited resources of networked wireless devices. This, however, comes at the expense of increased communication and the need for synchronization across the components over which the optimization problem is distributed. Asynchronous distributed optimization algorithms overcome this difficulty. We have developed such algorithms and shown that solutions of certain classes of optimization problems can be obtained with minimal communication (possibly none).

2. **Simulation-based optimization for real-time applications**. Simulation-based optimization can be computationally infeasible for real-time applications in a traditional stochastic programming setting where one first estimates an unknown objective function and then seeks to optimize it. We have studied a new idea in which we reverse this estimation-optimization order and have shown that, under certain conditions, this is indeed possible and leads to a substantial reduction in computational complexity.

3. **Temporal decomposition in stochastic optimization**. Decomposition over time amounts to the replacement of traditional "estimate-and-plan" approaches by "hedge-and-react" optimization. We have used event-driven (as opposed to time-driven) receding horizon techniques to reduce the solution of a highly complex stochastic problem to a number of smaller deterministic problems solved only when new data are obtained or new random events are observed.

4. **Abstraction and on-line gradient-based optimization**. Abstraction (or aggregation) schemes are used to preserve sufficient modeling accuracy to deliver at least near-optimal solutions to optimization problems which are otherwise intractable. This work has used Perturbation Analysis (PA) techniques to obtain gradient estimates from already available data without requiring stochastic models that are difficult to build. We have established a general framework for an Infinitesimal Perturbation Analysis (IPA) theory for stochastic hybrid systems and shown that IPA gradient estimators are characterized by robustness properties allowing us to apply optimization algorithms for the original system using performance gradient estimates of its abstracted version.

2. ACCOMPLISHMENTS AND NEW FINDINGS

1. Asynchronous Distributed Optimization.

In systems consisting of wirelessly networked resources, often energy-constrained, developing asynchronous distributed optimization schemes can ensure scalability and reduce the need for excessive communication. We have developed such a scheme which

is event-driven in that it limits communication to instants when some state estimation error function at a node exceeds a threshold. The broader question we are addressing is: "What is the minimal amount of communication required in a cooperative system for an optimization problem to still be solvable with no loss of its fundamental optimality properties?" We have proved that convergence of the scheme we developed to a (generally local) optimum is guaranteed. In our original analysis (during a prior AFOSR grant), this convergence result was derived assuming no communication delays and no noise in the process dynamics of nodes. This was extended [2] to problems where communication delays are not negligible, as long as they are bounded, and where process noise may be present, as long as it too is bounded. We have applied this approach to the class of "coverage problems" where a set of nodes is deployed in a region with the objective of maximizing the joint probability of detecting events occurring in this region. We have shown that in such settings communication cost is significantly reduced without any performance degradation. We have also studied the same problem arising after one or more events are detected and the corresponding sources must subsequently be tracked, while also maintaining an overall coverage. This leads to an optimization problem that combines coverage with source tracking for which we have shown that the same approach applies [8].

We have also developed an interactive simulation environment, available at http://www.bu.edu/codes/research/distributed-control/ through which we have performed experiments and tests related to the asynchronous distributed optimization framework described above and compared it to standard synchronous approaches. We also continue to use a laboratory test bed (created with partial support from a prior AFOSR grant) with small wireless mobile robots (Khepera III) acting as "agents" in a "real-world" cooperative setting (see http://www.bu.edu/codes/platforms/.)

2. Simulation-based optimization for real-time applications

Stochastic optimization is often infeasible for real-time applications in a traditional stochastic programming setting where one first *estimates* an unknown objective function (usually an expectation) and then seeks to *optimize* it. This is particularly true when simulation is involved and the computational burden of too many simulation runs is prohibitive. We have studied an approach in which we reverse this estimation-optimization order by first optimizing the objective function over specific sample paths and then estimating the distribution of the resulting optimal solutions, from which we can extract an optimal solution in probability (as opposed to optimal in expectation). This solution, if it exists, has the property of being optimal more frequently than any other solution. This leads to an alternative notion of "optimality in probability" as opposed to the usual "optimality in expectation."

We have shown (during a prior AFOSR grant) that for unimodular objective functions the optimal solution in probability exists and it is easy to obtain as the median of the distribution of sample path optimal solutions. Moreover, under certain conditions, it coincides with the traditional optimal solution in expectation. A key benefit of this approach is a reduction in computational complexity by orders of magnitude, creating new possibilities for stochastic real-time optimization. We first applied this approach to a class of scalar real-time optimization problems where the objective function is convex and our results (in publications included with reports for a prior AFOSR grant) show

substantial performance improvements over traditional optimality in expectation or conservative worst-case analysis. As part of this project, we tested this approach to the class of Linear Quadratic Gaussian (LQG) stochastic optimization problems, best known for the Kalman filter which is derived from it. In an LQG problem, we seek a sequence of Markovian policies which minimizes a quadratic optimization criterion subject to linear dynamics and Gaussian noise. This problem is known to have a solution which can be efficiently obtained by solving a Riccati equation. We studied this problem by seeking a policy that achieves optimality in probability along the lines of what was described above. Our main finding to date is that the policy obtained through the latter outperforms the one obtained through optimality in expectation, which is the classical Kalman filter.

3. Temporal decomposition in stochastic optimization

This part of the project has focused on making optimal decisions in a real-time stochastic setting in the absence of any information about the future at the time a decision needs to be made. To model the unknown future, we normally either build an analytical probabilistic model encompassing uncertainties or we resort to simulation. Building an analytical model is difficult because we must often make questionable assumptions, lack the necessary information, or resort to unreliable data to construct appropriate distributions. Simulation, on the other hand, is a time-consuming task. Both are "estimate-and-plan" approaches in which a policy is derived to dictate optimal decisions to make in real time as a function of an observed system state. An alternative is a "hedge-and-react" approach whereby we simply wait for a random event to occur and then react provided that the decision making process upon reaction is sufficiently fast relative to the random event frequency. In this approach, the process is viewed as deterministic in between randomly occurring events, amounting to a decomposition of a complex problem over time. Thus, at certain points in time, we solve an optimization problem over a given time horizon, and then continuously extend this time horizon forward. This gives rise to Receding Horizon (RH) optimization algorithms. We have used such algorithms to solve cooperative optimization problems arising when a team of "agents", e.g., Uninhabited Autonomous Vehicles (UAVs), must perform a mission consisting of tasks in an environment subject to uncertainties. In this setting, the optimization problem we solve at each point does not attempt to make any explicit assignments of agents to discrete tasks (e.g., visiting targets), but only to determine headings that, at the end of the current receding horizon, would place agents at positions such that a total expected reward is maximized. A key result we have obtained in past work is that the resulting agent trajectories actually converge to targets, despite the fact that our approach, by its nature, was never intended to perform any such discrete agent-to-target assignment.

In this project, we used this RH approach to solve new classes of problems that involve cooperative missions in uncertain environments. In [17] we provided specific solutions to missions defined through temporal logic specifications. In [14] we offered a solution to problems where agents must satisfy rendez-vous constraints in two-dimensional mission spaces in order to perform various tasks. Finally, in [22] we initiated a study of the "persistent monitoring" problem where agents must devise strategies to monitor a region by maintaining adequate information for every point in this region. We formulated a dynamic optimization problem aiming to minimize a measure of uncertainty over the region and proved that it can be reduced to a nonlinear parametric optimization problem which we were able to solve using some of the IPA techniques further discussed in the next section.

Another class of problems requiring real-time solutions in stochastic settings arises in dynamically allocating resources in transportation systems. We specifically studied the "parking problem" where a centralized system assigns and reserves an optimal resource (parking space) for a user (driver) based on the user's objective function that combines proximity to destination with parking cost, while also ensuring that the overall parking capacity is efficiently utilized. Our solution to this problem involves solving a Mixed Integer Linear Program (MILP) [20],[21]. In this case, the decision points at which the problem is solved in a RH manner are selected by combining time-driven and event-driven mechanisms. Simulation results have shown that this "smart parking" approach can achieve near-optimal resource utilization and significant improvement over uncontrolled parking processes or state-of-the-art guidance-based systems. Based on this approach, an iPhone application was developed in conjunction with a pilot study performed in a Boston University garage (see http://www.bu.edu/buniverse/view/?v=1zqb6NnD)

3. Abstraction and on-line gradient-based optimization

Under past AFOSR grants, we combined perturbation analysis and gradient-based optimization techniques to develop algorithms that are easily implementable for discrete event systems such as networks of different types. In this project, we were able to establish a general framework for an Infinitesimal Perturbation Analysis (IPA) theory [1] for stochastic hybrid systems to control and optimize their performance in a real-time setting that allows for uncertainties and changes in their operating environment. We have shown that stochastic discrete event systems can be abstracted to stochastic hybrid systems where IPA can be applied and have identified some robustness properties allowing us not only to optimize the abstracted version of the original system, but also to apply optimization algorithms for the original system using performance gradient estimates of its abstracted version [6]. Based on this new framework, we studied optimization problems for Stochastic Flow Models (SFMs) capturing the essential features of underlying resource contention problems with event-driven dynamics. We established unbiased IPA estimates for multiclass, multiobjective SFMs [4] and revisited a classic stochastic scheduling problem solution known as the "c-mu-rule" in a SFM setting to support the long-standing conjecture that this solution is independent of stochastic modeling assumptions [19],[7].

During this work, we came to the realization that previously intractable stochastic games can also be solved as multi-agent optimization problems so that system-centric solutions can be compared to user-centric ones and quantify the associated gap between the two, known as the "price of anarchy." Along these lines, we solved several stochastic resource contention problems [3], including the long-standing lot-sizing problem as a stochastic game for which we have formally proved that in this case the "price of anarchy" is zero [28].

3. PUBLICATIONS RESULTED FROM FA9550-09-1-0095

• Papers Published:

[1] Cassandras, C.G., Wardi, Y., Panayotou, C.G., and Yao, C., "Perturbation Analysis and Optimization of Stochastic Hybrid Systems", *European Journal of Control*, Vol. 16, No. 6, pp. 642-664, 2010.

[2] Zhong, M., and Cassandras, C.G., “Asynchronous Distributed Optimization with Event-Driven Communication”, *IEEE Trans. on Automatic Control*, AC-55, 12, pp. 2735-2750, 2010.

[3] Yao, C, and Cassandras, C.G., “Resource Contention Games in Multiclass Stochastic Flow Models”, *Nonlinear Analysis: Hybrid Systems*, Vol. 5, No. 2, pp. 301-319, 2011.

[4] Yao, C, and Cassandras, C.G., “Perturbation Analysis and Optimization of Multiclass Multiobjective Stochastic Flow Models”, *J. of Discrete Event Dynamic Systems*, Vol. 21, No. 2, pp. 219-256, 2011.

[5] Cassandras, C.G., and Paschalidis, I.Ch., “Optimizing the Transportation System’s Response Capabilities”, *J. of Homeland Security*, 2011.

[6] Yao, C, and Cassandras, C.G., “Perturbation Analysis of Stochastic Hybrid Systems and Applications to Resource Contention Games”, *Frontiers of Electrical and Electronic Engineering in China*, Vol. 6, 3, pp. 453-467, 2011.

[7] Kebarighotbi, A., and Cassandras, C.G., “Optimal Scheduling of Parallel Queues Using Stochastic Flow Models”, *J. of Discrete Event Dynamic Systems*, Vol. 21, No. 4, pp. 547-576, 2011.

[8] Zhong, M., and Cassandras, C.G., “Distributed Coverage Control and Data Collection with Mobile Sensor Networks”, *IEEE Trans. on Automatic Control*, AC-56, 10, pp. 2445-2455, 2011.

[9] Rohloff, K., Pal, P., Atighetchi, M., Schantz, R., Trivedi, K., and Cassandras, C.G., "Approaches to Modeling and Simulation for Dynamic, Distributed Cyber-Physical Systems", *Proc. of Workshop on Grand Challenges in Modeling, Simulation, and Analysis for Homeland Security (MSAHS-2010)*, March 2010.

[10] Cassandras, C.G., “Cooperative control and optimization in an uncertain asynchronous wireless networked world”, *Proc. of 18th IEEE Mediterranean Conference on Control and Automation*, June 2010.

[11] Yao, C., and Cassandras, C.G., “Perturbation Analysis of Stochastic Hybrid Systems and Applications to Some Non-Cooperative Games”, *Proc. of 2010 Intl. Workshop on Discrete Event Systems*, pp. 69-74, Sep. 2010.

[12] Yao, C., and Cassandras, C.G., “A Stochastic Hybrid System View at a Class of Non-Cooperative Games”, *Proc. of 26th IEEE Convention of Electrical and Electronics Engineers in Israel*, Nov. 2010.

[13] Yao, C., and Cassandras, C.G., “A Solution of the Lot Sizing Problem as a Stochastic Resource Contention Game”, *Proc. of 49th IEEE Conf. Decision and Control*, pp. 6728-6733, Dec. 2010.

[14] Yao, C., Ding, X.C., and Cassandras, C.G., “Cooperative Receding Horizon Control for Multi-agent Rendezvous Problems in Uncertain Environments”, *Proc. of 49th IEEE Conf. Decision and Control*, pp. 4511-4516, Dec. 2010.

[15] Zhong, M., and Cassandras, C.G., “Distributed Coverage Control and Data Collection with Mobile Sensor Networks”, *Proc. of 49th IEEE Conf. Decision and Control*, pp. 5604-5609, Dec. 2010.

[16] Wang, T., and Cassandras, C.G., “Optimal Discharge and Recharge Control of Battery-powered Energy-aware Systems”, *Proc. of 49th IEEE Conf. Decision and Control*, pp. 256-261, pp. 7513-7518, Dec. 2010.

[17] Ding, X.C., Belta, C., and Cassandras, C.G., “Receding Horizon Surveillance with Temporal Logic Specifications”, *Proc. of 49th IEEE Conf. Decision and Control*, pp. 256-261, Dec. 2010.

[18] Yao, C., and Cassandras, C.G., “Using Infinitesimal Perturbation Analysis of Stochastic Flow Models to Recover Performance Sensitivity Estimates of Discrete Event Systems”, *Proc. of 18th IFAC World Congress*, pp. 8217-8222, August 2011.

[19] Kebarighotbi, A., and Cassandras, C.G., “Optimal Scheduling of Parallel Queues with Stochastic Flow Models: The *c-mu*-rule Revisited”, *Proc. of 18th IFAC World Congress*, pp. 8223-8228, August 2011.

[20] Geng, Y., and Cassandras, C.G., “Dynamic Resource Allocation in Urban Settings: A “Smart Parking” Approach”, Proc. of *2011 IEEE Multi-Conference on Systems and Control*, Oct. 2011.

[21] Geng, Y., and Cassandras, C.G., “A New “Smart Parking” System Based on Optimal Resource Allocation and Reservations”, *Proc. of 14th IEEE Intelligent Transportation Systems Conf.*, pp. 979-984, Nov. 2011.

[22] Cassandras, C.G., Ding, X.C., and Lin, X., “An Optimal Control Approach for the Persistent Monitoring Problem”, *Proc. of 50th IEEE Conf. Decision and Control*, 2011.

[23] Wang, T., and Cassandras, C.G., “Optimal Control of Multi-Battery Energy-aware Systems”, *Proc. of 50th IEEE Conf. Decision and Control*, 2011.

[24] Kebarighotbi, A., and Cassandras, C.G., "Timeout Control in Distributed Systems Using Perturbation Analysis", *Proc. of 50th IEEE Conf. Decision and Control*, 2011.

• Accepted, but not yet published:

[25] Cassandras, C.G., and Panayiotou, C.G., "Concurrent Simulation for On-line Optimization of Discrete Event Systems", to appear in *Real-time Simulation Technologies: Principles, Methodologies, and Applications* (K. Popovici, P. Mosterman, Ed's), CRC Press, 2012.

[26] Wang, T, and Cassandras, C.G., "Optimal Control of Batteries with Fully and Partially Available Rechargeability", to appear in *Automatica*, 2012.

[27] Yao, C., and Cassandras, C.G., "Using Infinitesimal Perturbation Analysis of Stochastic Flow Models to Recover Performance Sensitivity Estimates of Discrete Event Systems", to appear in *J. of Discrete Event Dynamic Systems*, 2012.

[28] Yao, C, and Cassandras, C.G., "A Solution to the Optimal Lot Sizing Problem as a Stochastic Resource Contention Game", to appear in *IEEE Trans. on Automation Science and Engineering*, 2012.

• Submitted, but not yet accepted:

[29] Kebarighotbi, A., and Cassandras, C.G., "A General Framework for Modeling and Online Optimization of Stochastic Hybrid Systems", subm. to *4th IFAC Conf. Analysis and Design of Hybrid Systems*, 2011.

[30] Wang, T, and Cassandras, C.G., "Optimal Control of Multi-Battery Energy-aware Systems", subm. to *IEEE Trans. on Control Systems Tech.*, 2012.

4. PERSONNEL SUPPORTED

• Principal Investigator:

Christos G. Cassandras, Professor, Boston University

• Graduate Students:

- Minyi Zhong (PhD obtained, 2010)
- Chen Yao (PhD obtained, 2011)
- Ali Kebarighotbi
- Tao Wang
- Mohammad Moghadasi
- Jizong Shang
- Yanfeng Geng

The PhD dissertation completed by Minyi Zhong is entitled “Distributed Control and Optimization in Energy Limited Cooperative Systems”. It studies problems where optimization tasks are accomplished by deploying a distributed cooperative system, which consists of geographically distributed agents working on missions that require their combined efforts, with little or no central coordination. It identifies three key mission components: coverage control, data source detection, and data collection, and proposed an end-to-end solution framework. For coverage control, a gradient-based scheme was developed to maximize the joint detection probability of random events, taking into account the discontinuities introduced by obstacles and a limited sensing field of view. The optimization scheme requires only local information at each node and is suitable for distributed implementation. Using a modified objective function, the solution was enhanced to provide a more balanced coverage of the mission space when necessary. To facilitate reliable data source detection, a Bayesian occupancy grid mapping technique was adopted to recursively estimate the locations of potential data sources. Once a set of high occupancy probability locations is identified, a dual-objective optimization problem incorporating both coverage and data collection requirements is solved at each node. A simulator and two robotic testbeds were developed to implement and demonstrate the proposed framework. To reduce communication overhead in energy limited distributed cooperative systems, an event-driven communication scheme was developed focusing on how and when nodes should communicate in order to make their information exchange more efficient and thus save energy. Conditions were obtained under which the optimization process converges with asynchronous communication of state information among nodes. This asynchronous (event-driven) approach to the coverage control problem was shown to substantially reduce energy consumption while preserving the same performance as a synchronous algorithm.

The PhD dissertation completed by Chen Yao is entitled “Perturbation Analysis, Optimization and Resource Contention Games in Stochastic Hybrid Systems”. It considers general Stochastic Hybrid Systems (SHS) and develops a unified framework for carrying out Infinitesimal Perturbation Analysis (IPA) for such systems. Properties of IPA were established that justify its effectiveness in recovering useful performance sensitivity estimates. Subsequently, the dissertation concentrates on Stochastic Flow Models (SFMs), which form one class of SHS used to abstract the dynamics of many complex discrete event systems to provide the basis for their control and optimization. It extends prior work on single-user resource contention systems to multiclass settings that fully differentiate class-dependent performance metrics. A general framework was built based on multiclass SFMs to model stochastic resource contention systems, where multiple classes (users) compete for shared resources. The general IPA framework was applied to such systems to obtain performance gradient estimates for various user-specific objectives. This has enabled the study of a new user-centric optimization perspective, in addition to the usual system-centric viewpoint, and has led to the quantification of the difference between solutions of the two perspectives, commonly referred to as the “price of anarchy.” Two specific resource contention problems were studied. One is the admission control problem for a multiclass queueing system under a First Come First Served (FCFS) policy, where the admission thresholds of all classes are determined to optimize system performance. The other problem is the multiclass lot-sizing problem arising in the manufacturing production planning setting, where the objective is to obtain optimal lot sizes for all classes. For both problems, the general IPA framework was applied to the multiclass SFM abstractions to derive sensitivity estimates of performance metrics with respect to controllable parameters of interest, which are all proven to be unbiased, hence, reliable for control and optimization purposes. These estimates were then used to drive the on-line optimization of these parameters, and

simulation results are provided to contrast the solutions obtained through the “system-centric” and “user-centric” perspectives.

5. INTERACTIONS/TRANSITIONS DURING REPORTING PERIOD

Participation/Presentations at Meetings, Conferences, Seminars

C.G. Cassandras gave invited talks/ plenary addresses/lectures at the following meetings/organizations:

- *MIT LIDS Conf.*, Cambridge, MA, January 2009 (Plenary Address)
- AFOSR Grantee Meeting, Arlington, VA, March 2009
- CISE Emerging Technologies Day, Boston, MA, May 2009 (Invited Talk)
- IEEE CSS-UAE Workshop, Al Ain, UAE, November 2009 (Invited Talk)
- *48th IEEE Conf. on Decision and Control*, Pre-conference Workshop, Shanghai, December 2009 (Invited Talk)
- MathWorks Panel Discussion on "Designing Better Control Systems with Computational Models", Shanghai, December 2009 (Invited Talk)
- Politecnico di Torino, May 2010, Torino, Italy (Invited Seminar)
- *18th IEEE Mediterranean Conference on Control and Automation*, June 2010, Marrakech, Morocco (Plenary Address)
- *7th Intl. Conference on Electrical Engin., Computing Science, and Automatic Control*, September 2010, Tuxtla Gutierez, Mexico (Plenary Address)
- Universidad de los Andes, August 2010, Bogota, Colombia (Invited Seminar)
- CINVESTAV, September 2010, Mexico City, Mexico (Invited Seminar)
- Information Science and Technology Center, Colorado State University, October 2010, Fort Collins, CO (Distinguished Lecture)
- Colorado State University, October 2010, Fort Collins, CO (Invited Seminar)
- George Mason University, October 2010, Washington, DC (Invited Seminar)
- University of Cyprus, November 2010, Nicosia, Cyprus (Invited Seminar)
- AFOSR Grantee Meeting, Arlington, VA, April 2010
- IEEE-CSS sponsored Panel Discussion on "Preprint servers and how they can synergistically coexist with traditional publishers", Atlanta, GA, December 2010 (Invited Talk)
- NSF Workshop on "Ideas and Technology of Control Systems", Atlanta, GA, December 2010 (Invited Talk)
- *49th IEEE Conf. on Decision and Control*, Atlanta, GA, December 2010 (Invited Talk)
- *5th Annual DHS University Network Summit*, March 2011 Washington, DC (Invited Talk)
- IEEE CSS-UC Irvine Workshop, Irvine, CA, May 2011 (Invited Talk)
- *INFORMS 2011 Northeastern Conference*, Amherst, MA, May 2011 (Invited Talk)
- *4th HYCON2 School on Control of Networked and Large-Scale Systems*, Trento, Italy, June 2011 (Invited Lecture)
- *18th IFAC World Congress*, Milan, Italy, August 2011 (Invited Talk)
- *18th IFAC World Congress*, Panel Session on Education, Milan, Italy, August 2011 (Invited Panelist)
- IEEE CSS-UC Santa Barbara Workshop, Santa Barbara, CA, November 2011 (Invited Talk)
- NSF Workshop on "Ideas and Technology of Control Systems", Orlando, FL, December 2011 (Invited Talk)

Transitions

• *Dynamic Resource Allocation optimization algorithm used in developing a “Smart Parking”system with an iPhone application*

C.G. Cassandras and PhD student Yanfeng Geng developed an optimization algorithm used for a “smart parking” system using an application for the iPhone. The system was deployed in a garage pilot study at Boston University. A project is ongoing with Streetline, Inc. for potential commercial development.

6. NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

Provisional patent application: “Method and System for Dynamic Parking Allocation in Urban Settings” Application Number 61/521,424; filed 8/9/2011.

7. HONORS/AWARDS

C.G. Cassandras (Lifetime, selected):

Lilly Fellow (1991), Fellow of IEEE (1996), Fellow of IFAC (2008),

IFAC Harold Chestnut Prize (1999),

Distinguished Member Award, IEEE Control Systems Society (2006),

Editor-in-Chief of *IEEE Transactions on Automatic Control* (1998-2009)

Honors/Awards received during grant period:

- 2011 IEEE Control Systems Technology Award
- President, IEEE Control Systems Society, 2012
- Best Student (Yanfeng Geng) Paper Award Finalist, *2011 IEEE Multi-Conference on Systems and Control*
- 2011 IBM/IEEE Smarter Planet Challenge Prize, 2nd place (student team led by Yanfeng Geng)
- Poster Prize, 3rd place, (with Yanfeng Geng), *INFORMS 2011 Northeastern Conference*
- Distinguished Lecturer, Information Science and Technology Center, Colorado State University, October 2010
- Keynote/Plenary speaker in three international meetings/conferences